MATERIALS REQUIREMENTS FOR STANDARD LUNAR HIGHLANDS REGOLITH SIMULANTS AS DEFINED BY THE NASA SIMULANT DEVELOPMENT PROGRAM

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Introduction: The development of surface technologies for NASA's human and robotic lunar program beyond 2010 has begun. The multitude of projects underway and future ones will soon rely on the availability of lunar regolith simulant materials chosen to simulate the characteristics of lunar regoliths in order to design, test and qualify prototype hardware and flight equipment. The selection and development of standard lunar regolith simulants (SLRS) for the use of NASA technology programs was one of the main recommendations of the 2005 Workshop on Lunar Regolith Simulant Materials at Marshall Space Flight Center [1]. The realization of that objective is now underway through the NASA simulant development program at the Marshall Space Flight Center. The approach adopted to define materials requirements for standard simulants of regolith from the Highlands regions of the Moon will be presented along with a discussion of limitations inherent to such an endeavor.

Regolith of the Lunar Highlands – An incomplete puzzle: Apollo samples of soils from the regions of higher elevations of the Moon represent only a small fraction of the total collected mass. Only one mission, Apollo 16 was sent to a highlands region while Apollo 15 and 17 sampled highland/mare boundary sites. These missions found very complex geologic terrains compared to earlier Apollo sites. The variability of the highlands geology is ultimately reflected in the regolith (soil) formed by the continuous bombardment and comminuting of the local rocks and minerals [2]. The ubiquitous nature of these soil formation processes throughout the lunar surface lets us conclude that several physical characteristics are common to all lunar regoliths of similar maturity. These include grain size distributions, grain shapes and the presence of glass and agglutinate particles. While it is known that the fractional contents and compositions of agglutinate, glass and dust particles vary from site to site, their presence is a constant. The mineralogical and chemical nature of the highland regolith is a much more complex issue. Near-Infrared Reflectance Spectra data indicates that the mineralogy of highlands rock types is represented by various types of pyroxene, olivine, plagioclase, and glass [3]. Analyses of highland rocks reveal complex combinations of these minerals which do not allow depicting a comprehensive picture of the soil they produce.

Materials Requirements for Lunar Highlands SLRS: A lunar simulant is manufactured from terrestrial components for the purpose of simulating one or more physical and chemical properties of the lunar regolith. A requirements-driven approach is being developed for lunar highlands standard simulants. Our limited knowledge of the characteristics of lunar highlands soils on a global scale and the absence of equivalent materials naturally occurring on Earth forces us to make simulant requirements choices that are far less than perfect. In addition, any attempt to reproduce all the characteristics of these regoliths would only produce a very small quantity of a very expensive material. Alternatively, materials requirements for lunar highlands simulants are focused on selected physical, mineralogical, and chemical characteristics chosen to deliver a material that responds similarly to what is known of the behavior of lunar regolith when subjected to physical and mechanical handling as well as chemical processing.

Primary requirements for modal compositions include the representation of major lunar highlands minerals within similar ranges. These requirements are used to obtain adequate values for material properties that derive from mineralogy (e.g., hardness, major chemical compositions, bulk density). Additional primary requirements are defined for physical and chemical characteristics of major components of the regolith simulant such as shape, particle density, modal composition of agglutinate particles that can represent in excess of 50% of the regolith by volume. The combination of these requirements is intended to yield geotechnical

responses [4] and chemical behaviors of the same order as lunar highlands regolith. Secondary requirements can also be defined to ~~provide simulant materials that possess~~ additional properties considered critical for some hardware development and testing; these include concentrations of nanometer-size iron metal particles in glass phases, and concentrations of selected ions implanted in grains.

Lunar regolith simulants have a grain size distribution and distinct modal mineralogy at each size fraction that must be retained in order to match the target lunar regolith. As the sample size is reduced, at some point it is no longer representative. The deviation in properties is typically monitored by chemical analysis using major, minor, and trace element analytical data of progressively smaller sample sizes, and comparing these data with replicate analyses performed on bulk material. This problem is illustrated in the case of lunar simulant MLS-1 [5], where a ~10% variation in SiO_2 is observed, compared to a 160% variation for Cr. This is a chemical contrast effect, illustrating small differences in the major element Si for silicates, but large differences for the trace element Cr. Such variations play an important role in the behavior of the simulant when chemically processed for elemental extraction or transformation. The standardization of the modal composition of these simulants is also critical to obtain accurate simulation of phase diagrams and related properties such as viscosity at given temperatures and pressures. Similarly, geotechnical properties may be dominated by a large difference in mineral hardness, and rogue ~~grains would stand out in tests using too small a~~ quantity of material. The variability of simulant materials thus is an inherent property but must be taken into account for both quality control and for simulant use by the scientific and engineering community.

References: [1] Sibille L., Carpenter P., Schlagheck R., and French R. (2005) *Lunar Regolith Simulant Materials: Recommendations for Standardization, Production and Usage*, NASA Technical Publication (in press); Available at http://isru.msfc.nasa.gov/lib/workshops/lrsm2005.html. [2] McKay D.S. et al. (1991) *The Lunar Regolith*, Ch. 7 in "Lunar Sourcebook: A User's Guide to the Moon", Eds. Heiken G., Vaniman D. and French B., Cambridge Univ. Press. [3] Spudis P., and Pieters C. (1991) *Global and Regional Data about the Moon*, Ch. 10 in "Lunar Sourcebook: A User's Guide to the Moon", Eds. Heiken G., Vaniman D. and French B., Cambridge Univ. Press. [4] W.D. Carrier et al. (1991) *Physical Properties of the Lunar Surface*, Ch. 9 in "Lunar Sourcebook: A User's Guide to the Moon", Eds. Heiken G., Vaniman D. and French B., Cambridge Univ. Press. [5] Weiblen P.W., Murawa M.J., and Reid K.J. (1990) *Engineering, Construction and Operations in Space II*, ASCE, 428-435.